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From Evenk campfires to prehistoric hearths: charcoal analysis as a tool for identifying the use of rotten wood as fuel

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ABSTRACT

We present a new approach combining ethnoarchaeology and experimentation aiming towards a better understanding of prehistoric firewood use and management. The example of present fuel management practices among a residentially mobile group of Evenk Siberian reindeer herders, shows how ethnoarchaeology can provide an analytical background for the study of complex man–environment interrelations. Ethnographic observation confirmed in particular that the moisture content and structural soundness of the wood can be linked to hearth function: rotten conifers for instance, are used for hide smoking by several groups living in the boreal forests of the Northern hemisphere. Charcoal samples from an Evenk hearth fed with rotten *Larix cajanderi* (Siberian larch) showed a high proportion of microscopic features diagnostic of fungal alterations.

A series of systematic experimental combustions on *Pinus sylvestris* (scots Pine) confirmed the existence of a relationship between the frequency and the intensity of fungal alterations visible after the combustion and the initial state of the wood used in the hearth. The establishment of an alteration index allows now to take a new parameter, the structural soundness of the wood, into account when performing archaeological charcoal analyses.

1. Introduction

Over the past years, charcoal analysis or anthracology has been used in combination with complementary approaches combining palaeoenvironmental and socio-economical studies that seek to discuss firewood management (i.e., the process of exploitation and use of ligneous fuel resources in a given environment) among prehistoric societies (Théry-Parisot, 2001; Asouti and Austin, 2005). In this regard, ethnobotany has emerged as a methodological approach (Chabal, 1994; Ntinou et al., 1999; Ntinou, 2002; Moutarde, 2007). Ethnoarchaeology benefits charcoal studies by revealing the complexity and the variety of firewood management practices, which are deeply embedded within the cultural and ecological context they originate from Henry et al., (2009). The analysis of this variability of practices reveals general patterns that can help fuel management theory building. For instance, ethnographic work carried out under very different latitudes reminds us that the criteria according to which a society chooses its firewood cannot be reduced to a "simple" taxonomic selection: other characteristics, such as the calibre or the state of the wood (i.e., green, seasoned, rotten), are at least as important as the species (Théry-Parisot, 2001; Zapata Peña et al., 2003; Alix and Brewster, 2004; Dufraisse et al., 2007; Henry et al., 2009; Joly et al., 2009; Picornell et al., 2011).

The behaviour of wood during combustion is measured in terms of heat efficiency (e.g. flame height, ember production, combustion speed, ignition qualities) and calorific value (total quantity of energy released by weight unit of fuel). As they are defined by the chemical and physical characteristics of wood, these properties are species-dependent; however, they are significantly modified by the calibre and the state of the wood (moisture content, structural soundness) employed, which have a greater influence on the combustion process than the species itself (Théry-Parisot, 1998, 2001).

One of the goals of experimenting in anthracology is precisely to identify these parameters in order to characterize the combustion more accurately and, therefore, to clarify the criteria for past firewood selection and use (Théry-Parisot, 2001; Ludemann and Nelle, 2002; Moskal-del Hoyo et al., 2010; Théry-Parisot and Henry, 2012).

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Generally, the methodology employed is the standardized production under controlled conditions of charcoal reference sets, on which morphometric analyses are performed in order to verify the existence of given causal relationships between the characteristics of the wood *ante* combustion (moisture content, structural soundness) and the presence *post* combustion of certain specific characteristics e.g., radial cracks, cell wall deformations, collapsed cells, fungal hyphae (Théry-Parisot, 2001; Badal and Carrión, 2004; Allué et al., 2009; Théry-Parisot and Henry, 2012).

A few experimental studies dealing with fuel use have also included ethnographic reference sets consisting mainly of samples from hearths and/or fuels (Mallol et al., 2007; Tsartsidou et al., 2008; Lancelotti and Madella, 2012; Gur-Arieh et al., 2013), but they remain rare in the field of charcoal analysis (Ntinou, 2002; Henry, 2011).

Through an approach combining ethnoarchaeology and experimentation, this paper focuses on the selection of rotten conifers for the fire. First, we analyse the place of this practice in the firewood management system of nomad Evenks living today in the boreal forests of south-eastern Siberia. Then, we present the results of the charcoal study of two Evenk hearths, which showed significant differences in the frequency and the intensity of microscopic wood decay features attributable to fungi. Supplementary laboratory experiments involved the analysis of 1250 charcoal fragments from 10 batches of *Pinus sylvestris* in different states in order to verify that the soundness of the wood can be inferred through charcoal analysis. Our results lead us to propose a method based on the micromorphological characteristics of wood decay for assessing the soundness of the wood ante combustion (healthy vs. dead vs. rotten) and its implications for prehistoric charcoal analysis.

2. Firewood management practices among Evenki of Amur Region

2.1. Context of the study

One of the aims of the ethnoarchaeological fieldwork (project "Système Renne") was to obtain first-hand information from human groups living under cold environmental conditions similar to those prevailing in Europe during the Upper Palaeolithic and/or the Early Mesolithic, in order to evaluate the impact of mobility and strong seasonal constraints on fuel management.

Nearly three months were spent in the North-eastern part of the Amur Region (Eastern Siberia, Russian Federation), with Oročon-Evenks associated with the village of Ivanovskoe (Evenk name Ulgen). Most of the time was spent in the taiga, on the territory of a group of reindeer herders, in the valley of the Kharga River and its slopes (Fig. 1). This area, at an altitude of 700–900 m a.s.l., is covered by boreal forest in which larch (*Larix cajanderi* Mayr.) is the dominant species.

In order to observe as many fire-related activities as possible, two fieldtrips were taken at different times of the year (late winter/beginning of spring 2006 and end of summer/beginning of autumn 2007). Direct field observations were complemented by a series of oral history interviews about traditional activities, beliefs and wood uses (Henry et al., 2009; Henry, 2011).

2.2. Firewood management: main results

Four main vegetation types were present within 2 km around the Evenk campsites we visited: riverine vegetation (Evenk:

Fig. 1. Location of the ethnoarchaeological survey.

hulgakata), Dwarf pine (*Pinus pumila*) shrubland (*bolgi*), open larch (*L. cajanderi*) woodland (light-needled taiga, *bori*) and mixed spruce (*Picea obovata*) forest (dark-needled taiga, *ahign*).

According to our informants, 20 trees and shrubs are commonly used for woodworking, subsistence and medicine, but only three are employed as fuel. During our stays, even though the four vegetation types were frequented on a daily basis, only the light-needled taiga and more specifically, its main species, *L. cajanderi (irjaktè)*, was harvested for fuel. In addition, a clear disinterest in shrubby taxa and the avoidance of white birch (*Betula pendula*), believed to be harmful to humans and animals, was also noted.

The preference for *Larix* spp. (larch) is so strong that it influences settlement patterns i.e., the Evenks cite the direct availability of standing dead larch as one of the four fundamental criteria when choosing a campsite (Henry et al., 2009; Lavrillier, 2007).

Seasonal parameters also influence decisively firewood management in terms of fuel needs, which vary according to meteorological conditions but also to seasonal activities. Seasonality, mainly in terms of presence/absence of snow, also impacts the wood acquisition distances and means, the number and type of hearths and their function (Fig. 2). The quite simple organization observed at the winter camp (one indoor stove (*ohok*), fed mainly by standing dry but also green larch) changes in favour of a more complex pattern when the snow cover melts: fallen wood (*gara*) becomes available and can be used in the different outdoor campfires (*atu*) that are used throughout the snowless seasons, mainly for cooking, curing meat and smudging. Two types of features are directly linked to the cultural and economical context, i.e. smudging and smoking fires.

2.3. Smudge and smoke fires

Smudge fires (*samnin*) are inseparable from domestic reindeer. They burn constantly from late spring until early autumn to protect the herd from flying insects (Ingold, 1980; Lavrillier, 2007; Brandisauskas, 2007; Anikhovskij et al., 2012). The *samnin* are mostly fed with green wood, but other smoke-producing fuels such as fresh boughs, moist dead branches or mosses can also be used. Since the sole purpose of the fire is to produce smoke, the moisture and/or water content of the fuel are far more important than the species.

In the case of hide-smoking hearths, taxon and state of the wood are equally important: the fuel used is dark red, rotten and crumbling larch (*Larix* spp.), *hiltè* (Henry et al., 2009; Lavrillier, 2005;

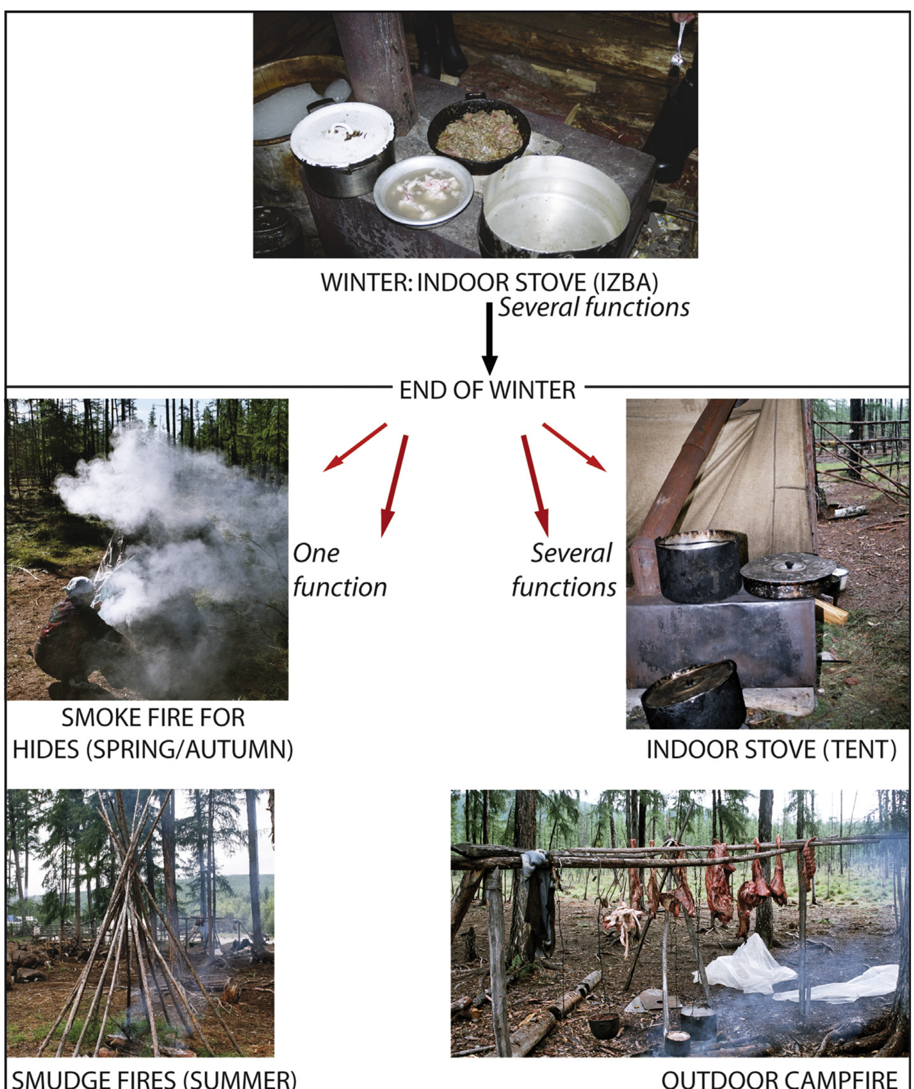


Fig. 2. Seasonality and activities linked to fire.

Brandisauskas, 2010; Anikhovskij et al., 2012). Burning coals are added to ignite a first layer of *hiltè*, which is then completely covered by a second layer, creating a low-oxygen, slow, smoky and smouldering combustion which leads to the formation and the adhesion of a thin brown–yellow layer (*njuksa*) on the hides' surface that waterproofs the hide and improves its resistance. The hide-smoking hearth we observed had been in use for the last four autumns, for a total duration of 6–8 h of combustion.

The information gathered among Evenks from Ulgen confirms that the notion of "good fuel" is relative and depends on several criteria such as resource availability, people's preferences and the final purpose of the wood (hearth type and function). Accordingly, the Evenks use one main tree species, *L. cajanderi* (larch), under different states: green or seasoned, healthy or degraded in order to respond to different hearth functions (Brandisauskas, 2007; Lavrillier, 2005 and pers. comm., 2007; Henry et al., 2009).

It is also worth noting that seasonality and mobility are deeply intertwined within the firewood management system. For example, hearth functions, by relating directly to the cultural and socio-economic context, also convey information about the season and therefore, the function of the occupation site. None of this information is accessible to the charcoal analyst through the floristic identification of the hearth remains, since *L. cajanderi* was the only species used in the Evenk camps we visited. On the other hand, a very specialized fire-related activity such as hide-smoking illustrates how the identification of the state of the wood may be crucial for the understanding of hearth function and its societal implications. According to previous work, the recognition of fungal decay features preserved on charcoal may allow diagnosing the use of degraded wood as a fuel (Théry-Parisot, 2001; Badal and Carrión, 2004; Théry-Parisot and Texier, 2006; Moskal-del Hoyo et al., 2010).

In order to test this hypothesis, bulk samples were taken from the hide-smoking hearth and from one smudge campfire; these correspond to the features the herders gave us permission to sample.

3. The preservation of wood decay features on charcoal

3.1. Previous research

Fungi expand inside the ligneous structure by producing spores, which develop into hyphae, altering the structure of carbohydrates (cellulose and hemicellulose) and/or lignin by depolymerization (Blanchette, 2000). According to their mode of degradation of the wood cell walls, fungal decay types are categorized into brown rot, white rot and soft rot (Table 1). However, a range of studies show that the identification of decay types on the grounds of micromorphological characteristics alone is open to question (Schwarze, 2007). The degradation of wood components lead to strength, weight and density losses whose progressive stages are microscopically identifiable through different types of cell wall alterations, i.e. cavities in secondary walls, cellular degradations or voids (Blanchette, 2000; Irbe et al., 2006; Schweingruber et al., 2006). Eventually, the decay of the cell wall components leads to the collapse of the initial cellular arrangement (Blanchette et al., 1997; Hakala et al., 2004; Levin et al., 2007).

Previous experimental studies show that fungal decay features, but also hyphae, are still visible after the combustion on charred wood samples inoculated with brown and soft rot under laboratory conditions (Théry-Parisot, 1998, 2001) but also on decayed wood collected in natural environments (Moskal-del Hoyo et al., 2010; Henry, 2011). The action of wood degradation agents has also been identified on archaeological charcoal from several European sites dating from the Middle Palaeolithic onwards (Théry-Parisot,

Table 1
Main characteristics of wood degradation by fungi, after Schwarze (2007); Blanchette (2000); Volk (2000); Lee et al. (2004).

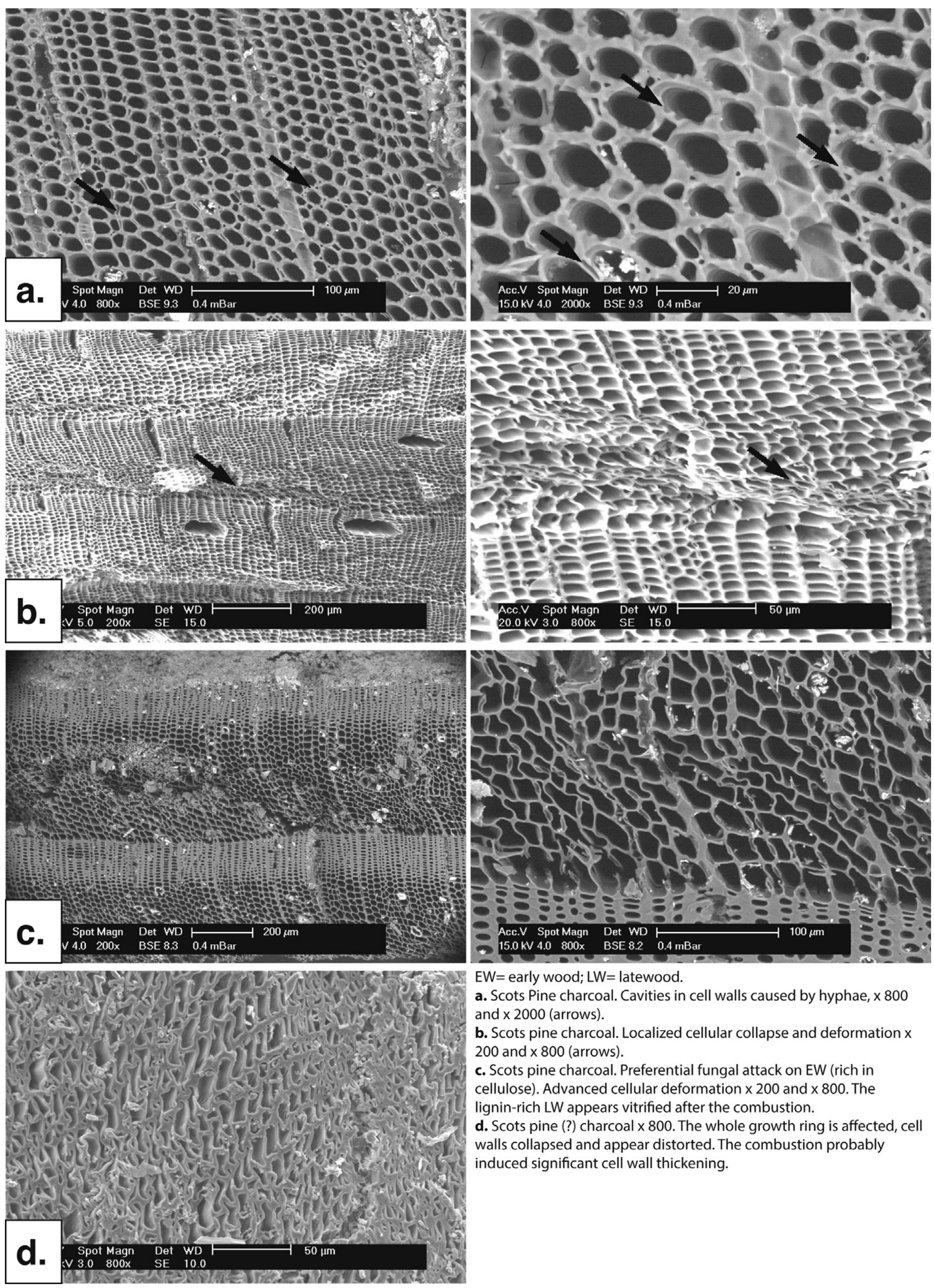
Agent	Brown rot: commonest in gymnosperms	White rot		Soft rot	
		Simultaneous rot	Selective delignification: rare in gymnosperms	Type I	Type II
Fungal action	Diffusion of degradative substances by hyphae	Degrade lignin, celluloses and hemicelluloses (fungal species and wood composition-dependent)		Degradation of cellulose and hemicellulose through hyphae; some lignin modification	
	Extensive breakdown of cellulose and hemicellulose; some lignin modification	Degradation in the immediate vicinity of hyphae	Degradation of hemicellulose and lignin by hyphae		
Macroscopic aspect of wood	Cubic fractures, shiny and brittle appearance, crumbling texture, colour reddish (cellulose degraded)	Fibrous, colour whitish (lignin degraded first)		Spongy texture of wood surface	
Microscopic characteristics	Loss of birefringence	Cell wall becomes thinner, degraded from the lumen outwards	Separation of individual cells from one another	Cavities with conically shaped ends in secondary walls	
	Leaves a network of residual lignin (i.e., earlywood is affected before latewood)	Delignification of the middle lamella or dissolution of lignin out of cell wall by hyphae		Gradual breakdown of the wood cell wall layer of the secondary wall	Progressive erosion of secondary walls but middle lamella not degraded
	Cell walls collapse and appear distorted	Localized erosion of secondary wall layers and middle lamella		At an advanced stage of decay, numerous cavities coalesce together	Discrete notches of cell-wall erosion
		Attack of all cell wall components lead to voids within the degraded wood			

1998, 2001; Badal and Carrión, 2004; Théry-Parisot and Texier, 2006; Marguerie and Hunot, 2007; Moskal-del Hoyo et al., 2010; Henry, 2011; Fig. 3). But it still remains difficult to interpret, as charring induces the disappearance and/or the modification of anatomical and biochemical characteristics, as well as the fragmentation of the material (Zicherman and Williamson, 1981; Prior and Gasson, 1993; Braadbaart and Poole, 2008). In other words, not all of the microscopic criteria defined for unburned wood are applicable to the study of charcoals; this is particularly true in the case of birefringence and thickness of the cell walls, which are significantly altered by the combustion. On the other hand, advanced decay features such as deformation, collapsed cell walls and gaps in wood structure are preserved after charring, and indicate that combustion of *altered* dead wood occurred (Théry-Parisot, 1998, 2001).

However, the available literature does not specify any quantification method that defines the minimal frequency of altered charcoals that would allow us to interpret a charcoal assemblage as the end-product of the combustion of dead, altered wood.

The meaning, in terms of assemblage interpretation, of these alterations can therefore be questioned.

Consequently, the aim of this study is to test the correlation between microscopic alteration features and the macroscopic state of the wood. In this context, the analysis of charred present-day material whose initial state is known is an indispensable aid for archaeological interpretation.



EW= early wood; LW= latewood.
a. Scots Pine charcoal. Cavities in cell walls caused by hyphae, x 800 and x 2000 (arrows).
b. Scots pine charcoal. Localized cellular collapse and deformation x 200 and x 800 (arrows).
c. Scots pine charcoal. Preferential fungal attack on EW (rich in cellulose). Advanced cellular deformation x 200 and x 800. The lignin-rich LW appears vitrified after the combustion.
d. Scots pine (?) charcoal x 800. The whole growth ring is affected, cell walls collapsed and appear distorted. The combustion probably induced significant cell wall thickening.

Fig. 3. *Pinus sylvestris* (Scots Pine) charcoal from the Mesolithic site Clos de Poujol (Aveyron, France), showing micromorphological characteristics of fungal decay *ante* combustion.

3.2. Charcoal analysis of two Evenk hearths

3.2.1. First observations and proposal of a methodology

Several charcoals from the *samnin* (Sample S) and the hide-smoking hearth (Sample N) were randomly selected and examined for decay features. Fresh manual cuts of the three sections of wood (transversal, radial and tangential) were observed with a 100, 200 and 500× magnification under a reflected light microscope using dark- and brightfield illumination. As expected, micromorphological decay features attributable to fungi were preserved, namely hyphae, perforated cell walls, cellular deformations of variable intensity and/or voids in the wood structure. They were most visible and clearly identifiable on the transverse section (TS), which led us to discard the longitudinal sections and develop a methodology based on the study of fungal alteration of the TS.

Maybe less expected was the fact that both hearths contained unaltered as well as altered charcoal fragments, the latter showing low to high and localized to generalized fungal alteration features. This variability appeared sometimes within a single charcoal fragment, and depended on the dimensions of the observation area and on the location of the cut.

In other terms, the study of one charcoal fragment, even if it shows advanced signs of decay by fungi, cannot define the macroscopic state of the branch or the wood assemblage it comes from. This observation points to the need for a quantitative approach in order to test if the study of a minimal number of charcoal TS would allow discrimination of samples S and N.

On the other hand, the intensity of fungal decay features does reflect the duration of the colonization of the wood by fungi (from the appearance of cavities and small voids, to cellular dissociation, deformation and collapse) and therefore, refers concretely to the decay of healthy wood into altered wood.

This suggests that it is important to associate finer qualitative attributes with the global distinction between unaltered and altered fragments. Therefore, and coherently with section 2 and our own microscopic observations of the decay features on charcoal, we propose a classification into four progressive intensities of alteration, referred to from now on as “Alteration Levels” (A.L., see Table 3): zero (0) low (1), medium (2) and high (3). A.L. 0 and 1 concern the incipient stages of colonization of wood by fungi, respectively no/very localized cell wall perforations (Figs. 4 and 5), A.L. 2 and 3 refer to the more global and structural cellular changes that intervene afterwards, such as the modification of the cell shape, cellular voids and deformations (Figs. 6 and 7), with the main difference between A.L. 2 and 3 being that decay is spatially restricted to certain areas and/or cellular deformations are less extensive for A.L. 2.

We studied the transverse sections of 150 charcoals from each Evenk hearth, picked randomly from among the 2–4 mm fraction (a size class commonly represented among archaeological charcoals). In order to verify that the minimal number of fragments to be analysed had been reached, we used a graphic display common in the field of anthracology, the saturation curve, a regression curve showing the floristic evolution according to the number of analysed fragments (Chabal, 1997; Chabal et al., 1999). Their general shape allows determining the heterogeneity of the sample, and their stabilization indicates that the optimal number of charcoal fragments to be taken into account for obtaining a representative sample is reached. Our version of these curves takes into account the percentages of the different A.L. per number of identified fragments.

3.2.2. Results: ethnographic material

The analysis of 150 charcoals for each fire shows that the total percentage of altered charcoals, as well as the proportions between the different A.L., are stable at around 100, but that the main tendencies are already perceptible after the study of 50 charcoals (Fig. 8a). These trends differ significantly between the two samples: sample S contained 34% of altered charcoal, of which the highest proportion is attributable to low A.L. (1), whereas sample N provided proportions of alterations making up more than 80% of the studied assemblage, which included a much higher proportion of 2 and 3 A.L. (Fig. 8b). The Mann–Whitney test confirms the difference between the two samples (for alpha = 1%). The statistical power of this test (macro developed by G. Le Pape, Tours, France), is excellent (95%), which means that the number of measurements (150) is more than satisfying to accept the Ha hypothesis (the two samples originate from different statistical populations). These first results allow us to propose the hypothesis according to which a correlation between the macroscopic and microscopic state of wood exists and is still detectable after charring. The purpose of additional experimental work is to verify this hypothesis, but also to acquire a finer picture of the alteration patterns.

3.3. Experimental validation

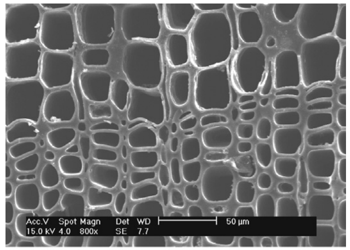
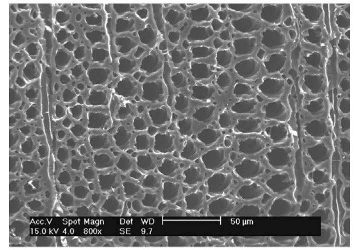
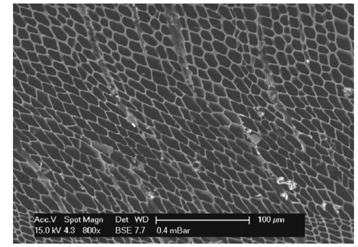
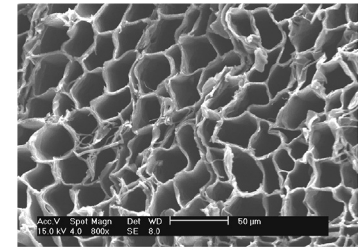
3.3.1. Protocol (Fig. 9)

Experimental combustion was conducted under strictly controlled conditions, by defining exactly the most relevant parameters. The wood was collected on the high plateaux of Alpes-Maritimes (France) where forest stands of *P. sylvestris* (Scots pine) in different states of decay were sighted (Table 2). The use of another species, *P. sylvestris* (and not *Larix*), for the experiments is justified by the fact that *P. sylvestris* is significantly more frequent than *Larix decidua* in European prehistoric sites, and that it possesses a resistance comparable to that of *Larix* spp. towards fungi and bacteria (Triboulot, 2002). On the field, small logs and branches

Table 2
Description of the ethnographic and experimental batches.

Label	Species	Soundness	Collected tree (T) or ground (G)	Anatomical element	General description
N (hide smoking fire)	*Larix cajanderi*	Rotten *(+ braises from healthy wood)*	G (+T)	Stump	Wood dark red, very altered, crumbling
S (smudge fire)	*Larix cajanderi*	Healthy *(+ dead branches)*	T (+G)	Branches, trunk	Healthy appearance + some greyish elements without bark
ST1; ST2 (standing dead)	*Pinus sylvestris*	Dead	T	Branches	General healthy appearance, locally greyish,
FD1; FD3 (fallen dead)	*Pinus sylvestris*	Dead	G	Branches	partially without bark
FD2 (fallen dead)	*Pinus sylvestris*	Dead	G	Branches	Wood greyish, mostly without bark
HRST (half-rotten)	*Pinus sylvestris*	Half rotten	G	Stump	Wood red-brownish, altered, no bark, beginning to crumble
R1; **R2** (rotten)	*Pinus sylvestris*	Rotten	G	Branches (?)	Wood red (R1) to dark red (R2), altered, crumbling, no bark
H1; H2 (healthy)	*Pinus sylvestris*	Healthy	T	Branches	Healthy appearance

Table 3
Microscopic criteria for the identification of the A.L.

Alteration Level (A.L.)	 A.L. 0	 A.L. 1	 A.L. 2	 A.L. 3
Alteration features	No micromorphological signs of decay	Cavities in cell walls; minor cell deformations	Perforated cell walls; cell deformation; and/or localized voids in cellular structure	Collapsed cell walls; major cellular deformations and/or important voids
Alteration intensity and presence on charcoal	None, *or* very localized A.L. 1	Low intensity *or* very localized A.L. 2	Medium intensity *or* very localized A.L. 3	High/very high intensity; generalized
Applying average	A.L. 0 + localized A.L. 1	A.L. 1 + very localized A.L. 2	A.L. 1 + at least equivalent surface of A.L. 2	A.L. 2 + at least equivalent surface of A.L. 3
General form of wood structure	Not affected	Not affected	Slightly affected; taxon remains identifiable	Affected taxon can be difficult to identify

in different states were sampled, from healthy looking, standing dead, to fallen, red, crumbling and rotten wood.

Previous to combustion, the wood was observed, measured and divided into three categories: standing dead wood (2 lots: SD1, SD2), fallen dead wood (3 lots: FD1, FD2, FD3), rotten wood on the ground (3 lots: HRST, R1, R2). One additional reference batch composed of healthy wood (H1 and H2) was also selected. Systematic replicas allow comparisons within a comparable experimental modality (respectively 2, 3 and 2 combustions). A total of

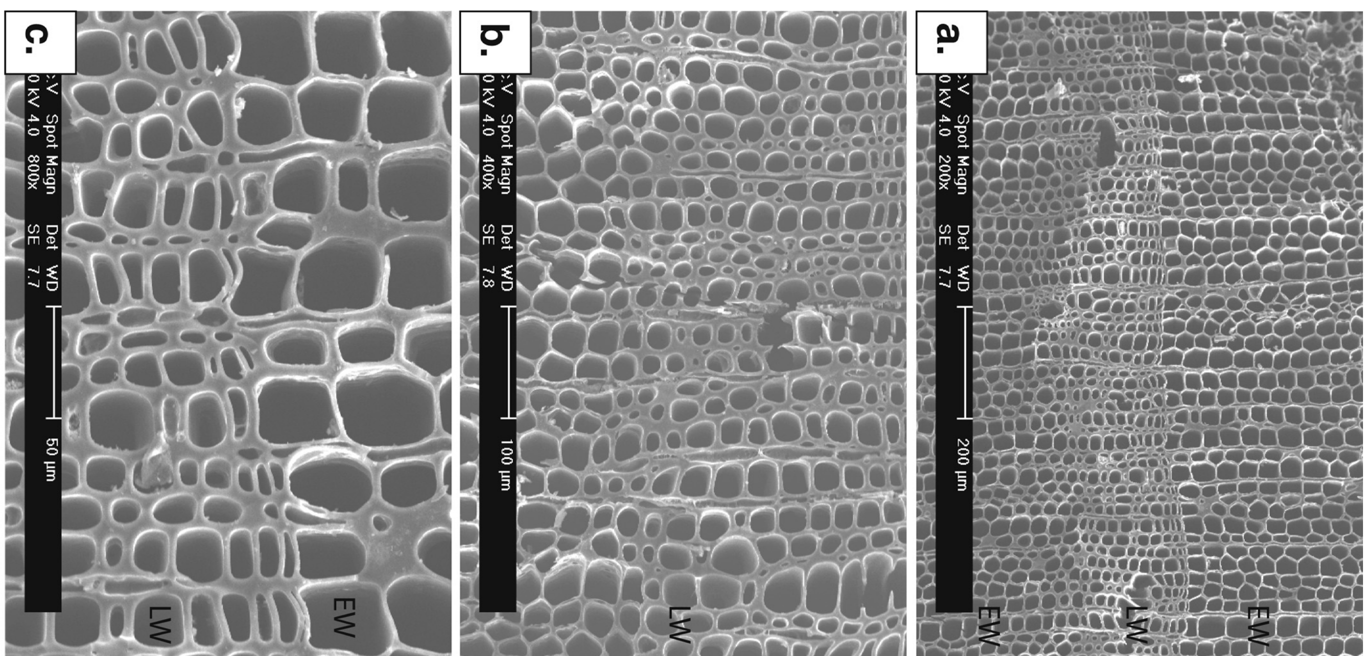
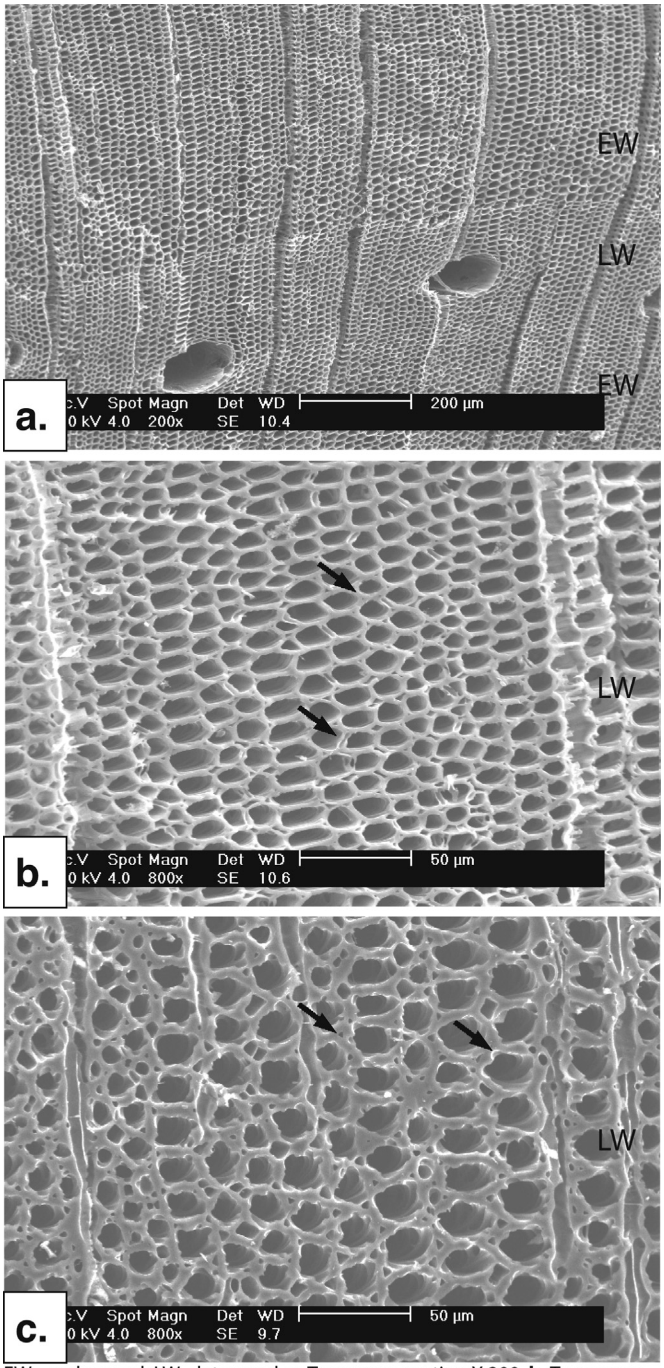


Fig. 4. Microscopic alteration level 0. EW= early wood; LW= latewood. **a.** Transversal section x 200. **b.** Transversal section x 400. **c.** Transversal section x 800. Note the squareness of the cells and the homogeneous shades and textures.



EW= early wood; LW= latewood. **a.** Transverse section X 200. **b.** Transverse section X 800. **c.** Transversal section X 800. Note the cavities around and inside the tracheid walls (arrows). The general shape of the cells is slightly altered.

Fig. 5. Microscopic alteration level 1.

10 experimental combustions were made in an open fireplace under laboratory conditions, in order to obtain samples charred under conditions that better resemble the archaeological reality (i.e. in an open fire where temperatures vary according to the state and calibre of the wood and its position in the hearth), but by limiting meteorological effects (wind, atmospheric humidity, fireplace shape, etc.). Fires were lighted with a blowtorch and temperatures were simultaneously recorded using sensors distributed within the wood.

After the combustion process, the totality of the charcoal was dry-sieved and the fraction of 2–4 mm was selected for systematic anatomical observation on the charcoal according to the method used on the Evenk samples.

Control sub-samples of each batch (slices 4 cm thick) were burned in a muffle furnace (wrapped inside aluminium foil and covered by sand). The samples were placed into the furnace one hour after the combustion temperature (500 °C) was reached for 45 min. Then, they were removed from the furnace and left under the sand until they reached room temperature and observed under the microscope according to the three sections of wood.

3.3.2. Results

All of the following quantitative results are synthesized in Fig. 10a.

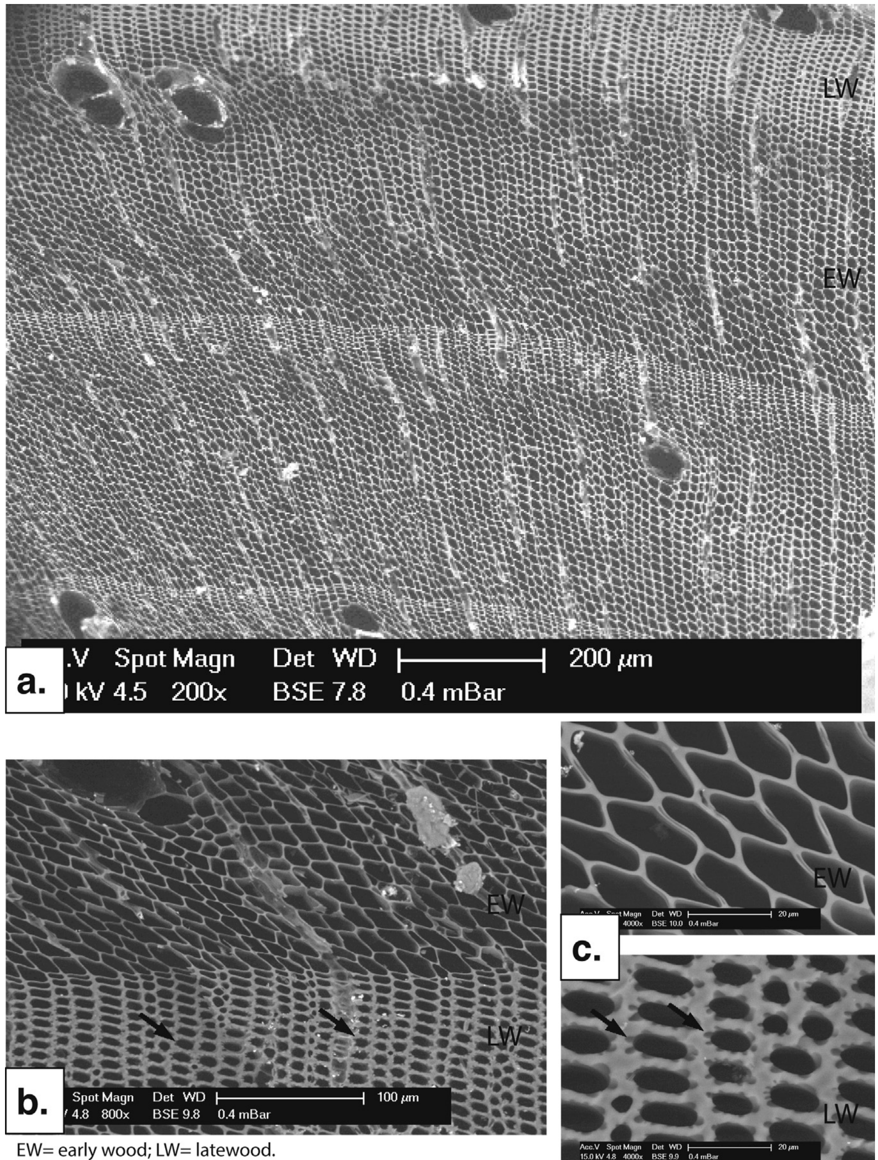
3.3.2.1. Healthy wood. Batches H1 and H2 are quite similar and characterized by a very high proportion of unaltered charcoals (84–86%). Low intensities of alterations are recorded (7–11%), as well as high A.L. (2 and 3); however, the latter do not exceed 10% of the assemblage. Altogether with the values obtained for sample S, this seems to indicate that green wood is not exempt from being locally colonized by degradation agents, but that alteration proportions and levels remain low.

3.3.2.2. Dead wood. The results obtained for dead wood show more variability. This can be explained by the fact that their macroscopic state ranged from healthy looking dead wood with its bark still on, to medium altered dead wood, characterized by a greyish colour and partly or completely exempt of bark (samples SD1 and SD2, FD1, FD2, and FD3). All these last samples share nevertheless common overall characteristics: a much lesser proportion of unaltered charcoals than healthy/green wood (between 31 and 59%), which results in a concomitantly higher proportion of alteration features. Among the latter, it is to note that A.L. 1 predominates (between 25 and 42%). A.L. 2 is also significantly higher than in healthy wood (15–22%); A.L. 3 remains quite low (1–8%). Interestingly, sample FD2, the only one composed from grey, fallen dead wood without bark, although following the general trend, shows the highest proportions of altered charcoals. According to these results, it does not seem possible to discriminate standing dead wood from not very decayed lying dead wood. This was expected, since they have the same macroscopic appearance.

3.3.2.3. Rotten wood. According to its description as a “half-rotten” stump, HRST shares microscopic characteristics with the dead wood batches (i.e., A.L. 1 = 39%) but with somewhat higher A.L. profiles: A.L. 0 drops to 16% whereas A.L. 2 raises to 33% and A.L. 3–12%.

These changes in the different A.L. proportions are even clearer for rotten wood assemblages, characterized by very low proportions of unaltered charcoal (3–6%) and the predominance of A.L. 2 (24–46%) and/or 3 (18–58%). The important variability of these percentages might be linked to the initial state of the wood batches used for the experiments, with R1 being less altered than R2, but may also remind us that the A.L. were established for the purpose of this study on specific micromorphological grounds only, A.L. 2 representing “medium” values which however already correspond to high, although localized, cell wall alterations. Accordingly to our initial hypothesis, rotten wood shows high frequencies of alteration, with A.L. 2 and 3 being frequently recorded.

These results show that a gradual tendency from healthy to rotten wood exists in the evolution of the proportions of the different A.L., which appears to follow our initial classification of the macroscopic state of the wood.



EW= early wood; LW= latewood.
a. Transversal section X 200. **b.** Transversal section X 800: cell wall deformation in EW and cavities in LW (arrows); defromed EW cells appear fragile and thin. **c.** Transversal section X 4000: localized A.L. 2 in EW + A.L. 1 in LW= global A.L. 2

Fig. 6. Microscopic alteration level 2.

3.3.3. *Statistical reliability of the results*

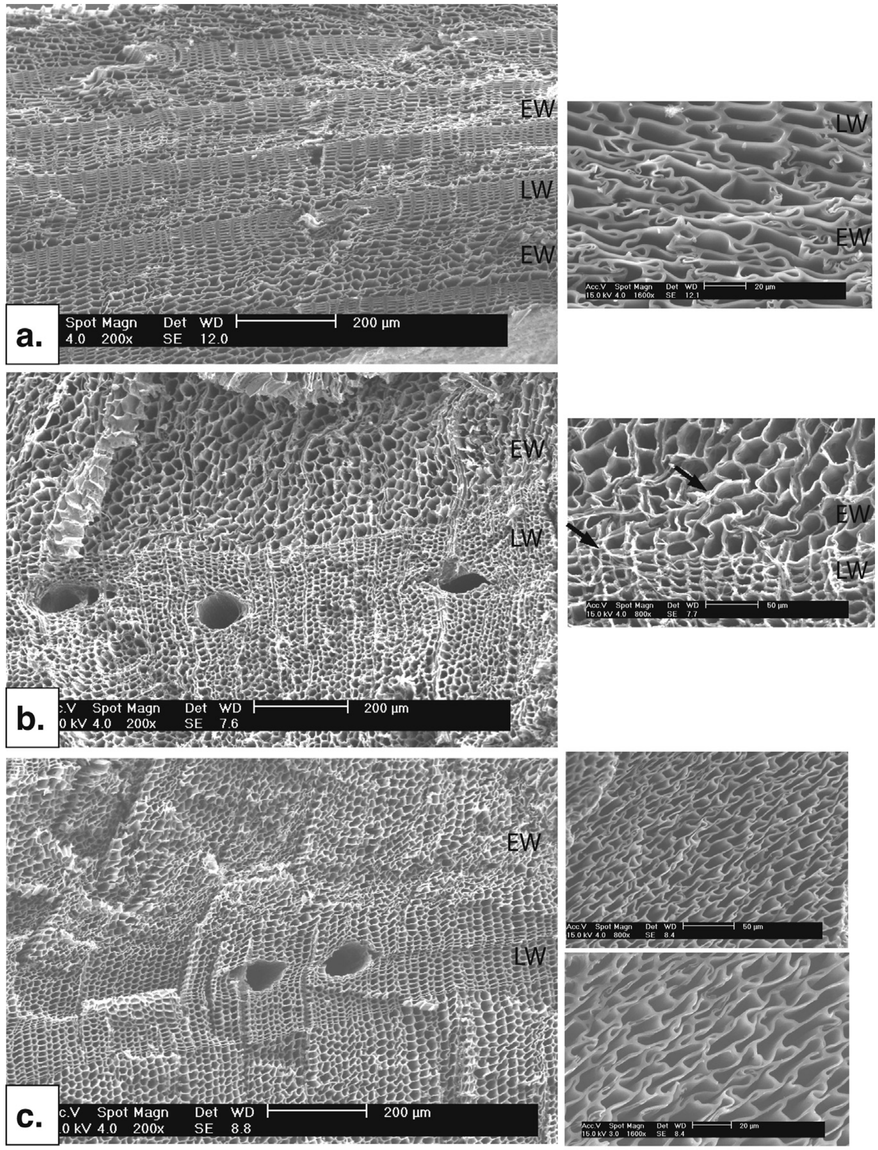
In order to verify the significance of these differences, we ran a statistical test of multiple pairwise comparisons. The resulting classification into seven groups confirms that at least two samples are clearly different (Fig. 10b). The relatively high number of statistical groups and their partial overlapping reflects in our sense quite accurately the gradual nature of wood decay. The classification order of the groups confirms the link between microscopic alteration features and initial macroscopic state of the wood (with H1 representing the healthiest lot and R2 the most decayed):

- Groups A and B: dominant healthy signature
- Groups C, D, E: dominant dead wood signature (low to medium decay);
- Groups F and G: dominant rotten wood signature

Accordingly, highly significant differences (p-values of 0.001 and lower than 0.0001) do exist between healthy, dead and decayed wood (Fig. 10c). The ethnographic samples fit quite well into this framework, with the *samnin* sharing characteristics of groups B and C, which reflects both the use of healthy (green) and dead wood. Sample N on the contrary is strictly associated with rotten wood (group F), which means that the ember added to ignite the hearth did not mask the main information, although it might have slightly impacted our results, i.e. a statistical difference with batch R2, the only sample composing group G, and quite high proportions of A.L. 0 (16%) when compared to batch R1 (6%) and R2 (3%).

3.4. *Proposal of an alteration index*

Experiments confirm that a quantitative study of microscopic Alteration Levels visible on charcoal assemblages allows



a. Transverse section X 200 and 1600. **b.** Transversal section X 200 and 800. **c.** Transversal section X 200, 800 and 1600. Deformed and collapsed cell walls dominate within the surface, where hyphae (arrows) can be frequent.

Fig. 7. Microscopic alteration level 3.

interpreting the initial macroscopic state of the wood. Statistical tests are well suited for determining the differences between the experimental reference sets and thus, for validating the proposed method. However, the more reference samples there are, the more statistical groups are potentially created, including groups whose differences may be statistically, but not actually, significant, at least for our purpose. In other terms, the thresholds between different states of wood have to be redefined by including the initial appearance of the experimental material and the corresponding alteration values on charcoal. For example, samples such as HRST or S, belonging to key-intermediary positions, can therefore be used to mark the limits between different alteration groups.

This is a necessary step for reaching the primary goal of any experimental approach, i.e. proposing a methodology allowing an easy integration and comparison of external data into the framework of the reference values.

In order to fulfil this objective, we created an alteration index based on the frequency of alteration (total %) as well as its intensity (% of each A.L.). The alteration index A*i* was obtained by adding all altered charcoals multiplied by their respective alteration level, divided by a theoretic maximal A.L. of 3 on each fragment, and multiplied by the total number of fragments studied: $Ai = ((nA1x1 + nA2x2 + nA3x3)/nTOTx3)$. We chose this calculation in order to obtain an index ranking from 0 to 1 that would facilitate the reading (Fig. 11). According to the resulting graph, a low index (<0.15) corresponds to a healthy batch of wood (A*i* of batch H1: 0.06). Medium values, as obtained for dead wood (from 0.2 to 0.34), signal light to medium alterations, whereas values higher than 0.5 characterize a batch of rotten wood (A*i* of $R1 = 0.56$; $N = 0.6$; $R2 = 0.8$). Very low and very high indices give a clear idea of the state of the large majority of the wood pieces composing the batch, whereas medium indices can result from the constant recording of medium values, or from average values of a mixture of wood in different states. However, a detailed examination of the different A.L. proportions comprising the samples (as shown in Fig. 8 or 10a) may lead to a better interpretation of the degree of alteration.

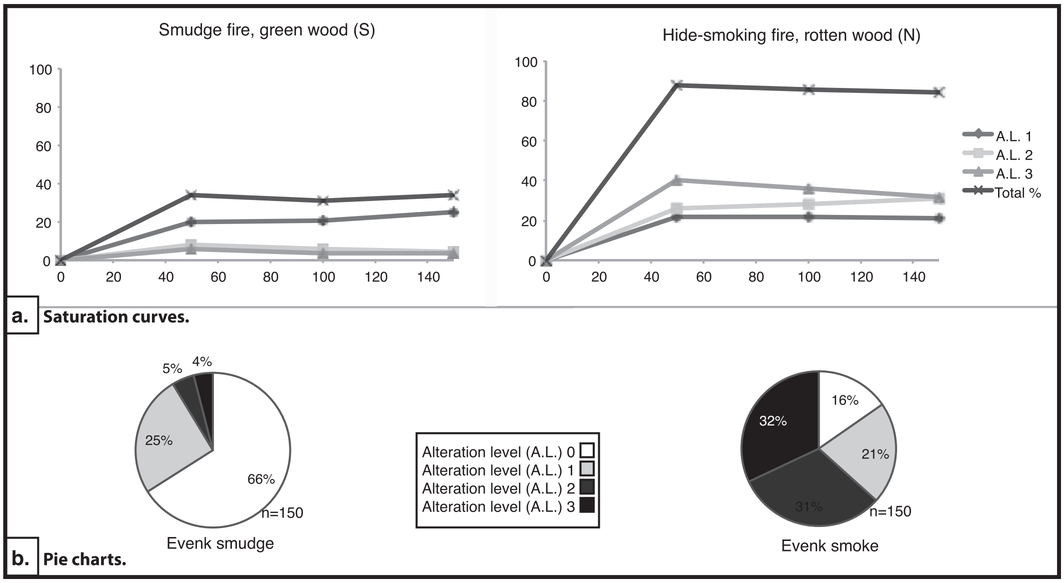


Fig. 8. Quantification of the different A.L. composing the ethnographic samples.

4. Discussion: from present-day to archaeological samples

4.1. Benefits of an ethno-experimental approach

The microscopic approach carried out on ethno-experimental charcoals allowed us to discriminate clearly highly altered wood from healthy but also from dead, lightly to moderately, altered wood. While the strictly experimental samples furnished a quite complete reference set applicable to the study of charcoal samples from coniferous woods, the results obtained for the Evenk hearths allowed a first evaluation of the approach of applying real-life conditions, which is always more complex than the experimental simulations. At the same time, the ethnographic material allowed us to confirm the validity of our method and its limits: in the

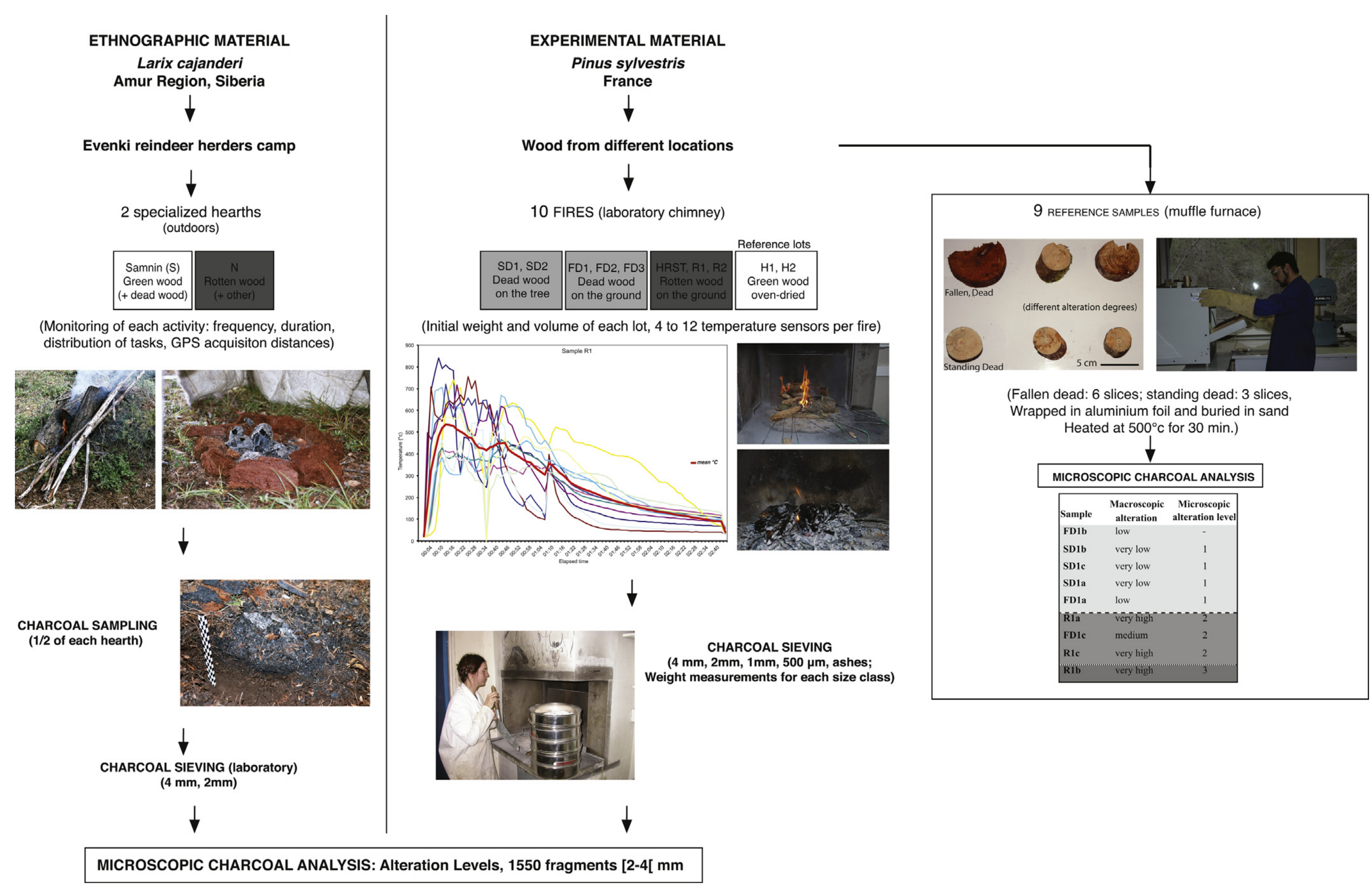
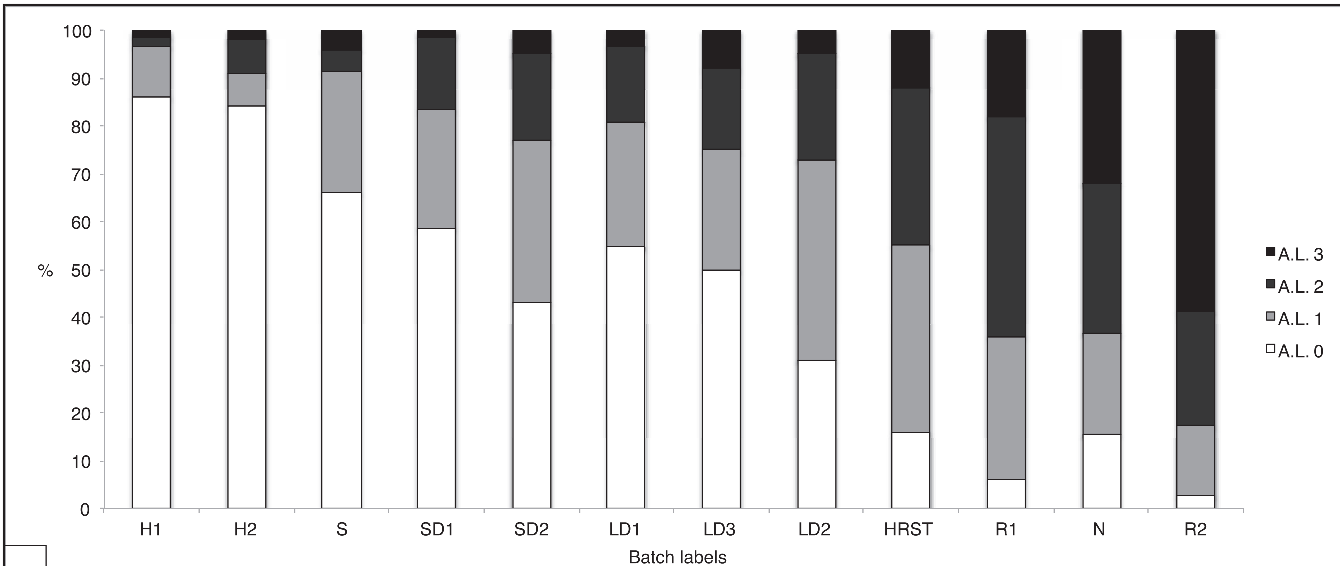


Fig. 9. Experimental protocol.



a. Proportions of A.L. per batch.

Sample	Frequency	Sum of ranks	Mean of ranks	Groups						
H1	150	62674,500	417,830	A						
H2	100	45244,500	452,445	A	B					
S	150	82479,500	549,863	A	B	C				
SD1	150	91202,500	608,017		B	C				
LD1	150	96430,500	642,870			C	D			
LD3	100	69810,500	698,105			C	D			
SD2	100	72002,500	720,025			C	D			
LD2	100	79576,500	795,765				D	E		
HRST	100	95210,500	952,105					E	F	
R1	150	156997,000	1046,647						F	
N	150	160268,500	1068,457						F	
R2	150	190128,000	1267,520							G

b. Corresponding statistical groups.

Significant differences:

	H1	H2	S	SD1	LD1	LD3	SD2	LD2	HRST	R1	N	R2
H1	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
H2	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
S	No	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
SD1	Yes	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes
LD1	Yes	Yes	No	No	No	No	No	No	Yes	Yes	Yes	Yes
LD3	Yes	Yes	No	No	No	No	No	No	Yes	Yes	Yes	Yes
SD2	Yes	Yes	No	No	No	No	No	No	Yes	Yes	Yes	Yes
LD2	Yes	Yes	Yes	Yes	No	No	No	No	No	Yes	Yes	Yes
HRST	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	Yes
R1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes
N	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	Yes
R2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No

Bonferroni corrected significance level: 0.0008

c. Statistical differences.

Fig. 10. Quantification and statistical analysis of ethnographic and experimental results.

specific and known context of Evenk pastoralist settlements, a "blind" study of such hearths, which are culturally significant, would lead to the clear identification of the nature and the function of the hide-smoking hearth, and, moreover, give seasonal information on the occupation of the settlement, since hides not usually smoked in winter (Henry et al., 2009). On the other hand, the characterization of the degradation features present on the charcoals from the *samnin* did not lead to a precise interpretation of its function, since it only indicated a globally healthy to very slightly altered wood. In such cases, other approaches focussing not on the soundness, but on the moisture content of the wood (green/seasoned), may be more adapted once fully developed (Théry-Parisot and Henry, 2012).

Given the potential problem that was identified, of mixtures of wood in different states, the archaeological situation appears even more complex in terms of charcoal mixtures and/or palimpsests in the archaeological layers.

4.2. From the charcoal deposit to its interpretation

More specifically, scattered charcoal assemblages are the commonest within archaeological sites. Since they usually synthesize

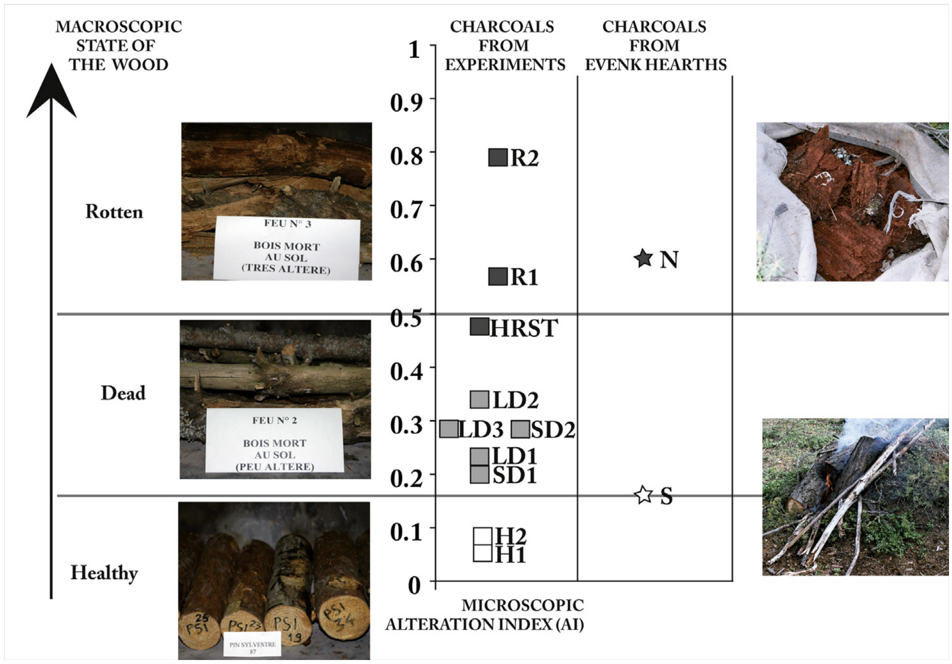


Fig. 11. Alteration Index (A.I.) of the ethnographic (stars) and experimental (squares) charcoal assemblages.

the episodes of wood procurement and use that occurred during the formation of the archaeological layer, they are well suited for palaeoenvironmental reconstructions (Chabal, 1997). Applying our method to such assemblages may be questionable in the sense that it is difficult to assess whether "medium" *Ai* obtained on heterogeneous samples may correspond to a recurrent pattern in wood selection strategies (i.e. systematic acquisition of dead wood) or, on the contrary, the sum of alternating selection practices (healthy plus rotten plus dead wood). On the other hand, extremely low or high *Ai*, even obtained on scattered charcoal, may accurately reflect the main soundness of the wood.

In any case and for all types of charcoal deposits, the decision regarding when to study and how to interpret the state of the wood has to be made in the light of the nature of the charcoal remains (preservation state, quantity, origin), but also of the quality and completeness of the archaeological data (possibility of spatial analyses, availability of data about site function and/or duration of occupation, etc.).

Moreover, if our experimental results are valid for charred material, (i.e. already altered by the combustion process), we cannot discard straightaway the possibility of a differential post-depositional behaviour of charcoal fragments according to the state of the wood they originate from. Experimental simulations of the taphonomic processes affecting charcoal (Théry-Parisot, 1998, 2001; Théry-Parisot and Chabal, 2010; Chrzavzez, 2013; Chrzavzez et al., 2014) tend to show that even though charcoals from decayed wood seem to fragment faster during processes in which water is involved (i.e. desiccation/waterlogging and freeze—thaw), they are not systematically more vulnerable when compared to charcoals from healthy wood. Nevertheless, it would be interesting to know if the observed fragmentation equally applies to the charcoals composing each sample, or if it affects the fragments with the highest A.I. first, modifying our image of the alteration patterns. This last issue should be approached experimentally, but it does not inhibit us from beginning to test our method on archaeological material, especially since other multiple factors may influence the preservation of charcoal deposits to a higher extent than the initial state of the wood. Among these, direct exposure to weathering processes and mechanical pressures such as trampling highly affect charcoal (Chrzavzez et al., 2014). Therefore, and until new experimental data are available, a good knowledge of the taphonomic history of the site and its features as it can be provided by geo- and micromorphological analyses can help determine the potentially more suitable sampling contexts. For all the reasons cited above, the approach presented here should be transposed very carefully to archaeological situations. It seems to be especially pertinent for the study of punctual, chrono-stratigraphically and spatially secure combustion features. The very possibility of proposing socio-economical interpretations for charcoal concentrations — which are often considered improper for palaeoenvironmental reconstructions because of their limited nature (Chabal, 1997; Chabal et al., 1999; Asouti and Austin, 2005)- re-establishes the study of hearths as an important part of charcoal analysis.

4.3. Firewood in different states: archaeological implications

A couple of decades ago, the state of the wood used in ancient hearths was already considered in anthracological theory-building as a parameter influencing past firewood management systems in terms of human choices and behaviours, which *in fine* affect our perception of past vegetation (Shackelton and Prins, 1992). More recent postulates on the implications of the use of dead and rotten wood by prehistoric groups also concern acquisition strategies and techniques and specific hearth functions (Théry-Parisot, 1998, 2001, 2002a, 2002b; Théry-Parisot and Meignen, 2000; Théry-Parisot and Texier, 2006; Henry et al., 2009).

4.3.1. State of the wood, fuel collecting strategies and palaeoecological reliability

At a theoretical level, prehistoric firewood collecting strategies can be defined in terms of cutting green wood or gathering dead wood (Théry-Parisot, 1998, 2001, 2002) and their modalities, such as a pronounced taxonomic choice or, on the contrary, the use of a

broad spectrum of species (Henry et al., 2009). Observing fuel acquisition and use in real-life conditions nuances this general theoretical framework and illustrates how certain practices can be directly linked to environment and culture which play, at several levels, a significant role in human decision-making. For instance, the relatively low biodiversity of the boreal forest and especially, of the open *L. cajanderi* (larch) woodland, is reflected in the limited floristic composition of Evenk hearths, but the latter can only be explained completely by the strong preference for larch shared by several Evenk groups (Lavrillier, 2007; Brandisauskas, 2007; Anikhovskij et al., 2012). In sum, we are in a situation of low biodiversity but with a biomass abundant enough to allow basing firewood management on a differential use of the state of the wood as a response to well-defined needs.

According to our ethno-experimental results, a healthy wood signature corresponds to dominant proportions of green wood, or testifies to the capacity of humans to dry wood in optimal conditions, since standing dead wood collected in the forest showed higher alteration patterns. Therefore, a healthy signature allows highlighting the practice of woodcutting, which implies that effort was put into the acquisition of standing trees.

In anthracology, this practice is traditionally opposed to wood gathering, which refers to the selection of dead wood, i.e. the "necromass" mostly represented by lying dead wood of small calibre, but also by fallen trees and standing dead wood (Théry-Parisot, 1998, 2001, 2002; Henry et al., 2009; Théry-Parisot et al., 2011). Dead wood is considered appropriate for hunter–gatherer short-term occupations since it is already seasoned and thus, directly useable in the hearth. The selection of available dead wood for immediate use may imply that the state of the wood is more important than the taxon and therefore, limits a choice of the firewood based on the species (which, by extension, may lead to a better palaeoecological reliability of the charcoal assemblage). This behaviour, close to what Shackelton and Prins (1992) defined as "the principle of the least effort" (PLE), can be identified archaeologically by combining traditional anthracology with A.L. studies. The higher the *Ai* appears, the lower is the probability that sound wood was employed, which may be linked to high proportions of wood at an advanced stage of decay in the local environment, reflecting strategies focused on the acquisition of fallen dead wood. Fallen wood is easier to obtain without tools such as axes or adzes; however, it represents only a part of the whole necromass, which itself is less abundant than green wood. In other terms, greater distances have to be covered for acquiring dead wood (Théry-Parisot and Meignen, 2000). This is corroborated by our ethnographic observations among Evenks, with green wood acquisition distances representing ¼ or less of the distances covered to harvest standing dead wood, whereas fallen dead wood represented only a very small part of the fuel since all of it was used on the first days of occupation. Moreover, we already saw that fallen wood can become unavailable due to an important snow cover, which makes it easier for Evenks to harvest standing trees of small diameter with a small axe, a good knife or even manually, when they need to make a campfire while they are on herding or hunting expeditions (Henry et al., 2009; Lavrillier, pers. comm).

These examples show how the identification of the state of the wood provides some insights into acquisition techniques and distances, contributes to the formulation of hypotheses about the palaeoecological reliability of the charcoals and may even be complementary to seasonality studies.

4.3.2. State of the wood and hearth type and function

The preferred fuel of the Evenks is standing dead larch (*Larix* sp.), because it provides more heat than green wood. It is a good fuel for the stove, since it produces a reasonable amount of ash (Henry, 2011). This opinion changes radically according to the combustion feature (stove vs. open fire) and its function (specialized vs. unspecialized). A greater variability of states and sometimes, of species, are used in open, outdoor campfires, since (i) log calibre and ash production don't matter and (ii) they have more general, or several successive functions. At the Evenk autumn camp, for instance, the main campfire was fed with healthy looking dead wood only when more heat needed to be obtained for cooking; otherwise it functioned basically as a *samnin*.

On the other hand, specialized (i.e. mono-functional) outdoor fires require specific fuels that ensure the success of the thermal treatment. Conifers, for instance, are absolutely not adapted to the smoking of fish (which was not performed during our stay) since their use results in a black colour and a bitter taste. In the same way, *hiltè* is the only adequate fuel for smoking hides. Its acquisition is an active process that can take up to five times longer than cutting standing wood, since wood at this stage of decay can be difficult to find in the local environment. In such contexts, it appears that it would be difficult for a "random" dead wood collecting strategy to exceed *Ai*s of 0.5; therefore, a higher *Ai* may indicate a deliberate use of rotten fuel for specific activities, as shown by a range of ethnographic studies. Indeed, several people all over boreal Siberia and northern America take advantage of the diminished combustion properties of rotten wood for smoke production. In northern environments dominated by conifers, spruce (*Picea* spp.), larch (*Larix* spp.) and/or pine (*Pinus* spp.) are burned rotten for hide smoking, but also for repelling mosquitoes (Osgood, 1936; Nelson, 1986; Beyries, 1999, 2002, 2008; Alix and Brewster, 2004; Brandisauskas, 2007, 2010; Lavrillier, 2007; Henry et al., 2009; Anikhovskij et al., 2012). In more southern vegetation areas and/or other cultural contexts, they are used concomitantly with -or replaced by-other fuels (Binford, 1967; Skibo et al., 2004; Skibo and Fisher, 2009). Thanks to our method, it becomes possible to investigate archaeological testimony to this widespread phenomenon and to contribute to a better knowledge of the technical traditions linked to the use of fire.

Therefore, we propose that charcoal assemblages from conifer-dominated environments with a very high *Ai* characteristic of crumbling, rotten wood, may in particular be investigated along with other archaeological evidence (shape of the hearth, burned artefacts, use-wear analyses) in order to formulate hypotheses regarding different hearth functions.

5. Conclusion

Ethnographic analogy helps us to understand in what ways firewood selection and hearth function are interconnected within given socio-economical contexts. They also broaden our research perspectives and experimental datasets by showing through concrete examples, in which all the parameters of firewood management systems are observable, how hearth function can be linked to site function and how these parameters can be revealed through archaeological charcoal analysis.

In light of the coherence of the results obtained both on ethnographic and experimental material, the microscopic characterization of biological alteration of charcoal has contributed to the understanding of the relationship between macroscopic and microscopic alteration features on *P. sylvestris* and *Larix*.

The alteration index, calculated from the proportions of altered charcoals and alteration levels per assemblage, allows us to formulate archaeological hypotheses concerning the macroscopic state of wood *ante* combustion. The perspective of being able to discuss the physical integrity of the wood used in ancient hearths is particularly promising for archaeological research, since it allows highlighting specific hearth functions, therefore contributing to the

identification of site function. More generally, an advanced analysis of the fuel used in archaeological combustion structures contributes to their techno-functional characterization, which is fundamental in apprehending the technical motivations and limitations of past groups. It is complementary to ethnographic analogy, as both approaches can be combined to better understand the variability of past and present practices and avoid too narrow interpretations.

Since not all species respond equally to fungal attacks, further studies will focus on other taxa such as different kinds of hardwoods or other conifers with different resistance to fungi.

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